Centrifugal Filter for Aerosol Collection

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Air filters collect particles by the mechanical collection mechanisms, namely, inertia, interception, gravitational settling and Brownian diffusion. There exists the most penetrating particle size (MPPS) in submicron size range for which none of the collection mechanisms work effectively. In this study, we propose, a new type of filter named as "centrifugal filter", which collects aerosol particles by centrifugal force together with the conventional mechanical collection mechanisms. The centrifugal filter proposed in the present work may be rotated by a motor or compressed air. Air passes through the filter in the axial direction of filter rotation. The filter rotates so does the air embedded in the filter, and therefore centrifugal force exerts on particles. In addition to the mechanical collection mechanisms, small migration of particles due to the centrifugal force enhanced the collection efficiency of submicron particles significantly without increasing the pressure drop. The performance tests of centrifugal filter were conducted by changing the fiber diameter, the air flow velocity and the rotation speed. We found that the collection efficiency of filter is enhanced significantly by rotating the filter without increasing the pressure drop and that the filter efficiency is well predicted by the conventional filtration theory accounting for the centrifugal force.

1. INTRODUCTION

Air filtration is the simplest and economical means to remove particles from air and other gases. The air filters collect particles by the mechanical collection mechanisms, namely, inertia, interception, gravitational settling and Brownian diffusion, but there exists the most penetrating particle size (MPPS) in submicron size range for which none of the collection mechanisms exert effectively (Hinds 1982). Electret filters may be used for capturing submicron particles at a high collection efficiency without an increase in pressure drop (Brown et al. 1988; Romay et al. 1998). However the degradation of collection efficiency is inevitable due to the accumulation of particles (Otani et al. 1993). Recently, nanofiber filters have become of great interest because they may have a high collection efficiency at a low pressure drop because of slip flow effect. However, at present, the manufacturing processes of nanofiber filters are not simple and not mass productive (Barhate and Ramakrishna 2007) so that their prices are relatively high and therefore they are not widely used. We need some other collection mechanisms which can be combined with the mechanical collection mechanisms.

The present paper proposes a new type of filter named as "centrifugal filter" which collects aerosol particles by centrifugal force together with the conventional mechanical collection mechanisms so that the centrifugal filter can achieve high collection efficiency and low pressure drop at the same time. The attempts to combine centrifugal force and mechanical collection mechanisms have been made previously and there are commercially available rotary filters (Sintokogio, Ltd. 2015) at present. The biggest difference between the centrifugal filter proposed in this work and the conventional rotary filters is such that in the centrifugal filter the centrifugal force exerts particles in the direction perpendicular to the airflow and the targeted particle size of collection is in submicron range. In the conventional rotary filters, the centrifugal force exerts parallel to the airflow and the targeted particle size of collection is mostly several micrometers. By letting the centrifugal force act perpendicular to the airflow, the presently developed centrifugal filter possesses many advantages over the conventional ones, i.e., depth filtration with a long residence time of particles in the filter, and no shedding of particles into filtered air.

The lab-scale centrifugal filter was designed and constructed and the fundamental collection characteristics of centrifugal filters were studied both theoretically and experimentally.

2. COLLECTION EFFICIENCY OF CENTRIFUGAL FILTER

The centrifugal filter proposed in the present work is such that the filter is rotated by either a motor or by compressed air. One of the basic designs of centrifugal filter is shown in Figure 1. A cylindrical filter with the inner radius, R_1, and the outer radius, R_2, and the length, L, is placed in a pipe and air is passed through the filter with volumetric flow rate of Q. The filter rotates at the rotation speed of ω, so the centrifugal force, F_c, exerts on particles. In addition to the mechanical collection mechanisms, small migration of particles due to centrifugal force may significantly enhance the collection efficiency without increasing the pressure drop. If we realize the centrifugal filter, the merits are; 1) we may create zero-pressure drop air filter by combining the filter with a fan, like FFU, 2) no motor is required if filter is rotated by compressed air, A propeller may be attached to the rotation axis of centrifugal filter and placed in an air duct, the filter connected with a propeller can be rotated by the air flow without a motor. 3) there would be no shedding of collected particles because reentrained particles can be recovered in the radial direction – this is a great advantage of centrifugal filter in the application as a mist eliminator, 4) it may be easy to build self-cleaning filter – operating like a washing machine. By rotating a filter, we have three more parameters (R_1, R_2 and the rotation frequency: $f=\omega/2\pi$) in addition to the conventional static air filters. By tuning these parameters, it may be possible to design a centrifugal filter with a given dimension that satisfies the requirement for collection efficiency and pressure drop at a given aerosol flow rate.

The expected application of centrifugal filter is versatile, e.g., removal of PM2.5, removal of haze in work places, vacuum cleaner, ventilation fan, mist eliminator for oil droplets, recovery of powder products, removal of reentrained droplets from scrubber. Furthermore, the centrifugal filter can be used for the classification of particles since we may vary the cut-off diameter solely by changing the rotation speed of the filter. One of the most important applications of centrifugal filter is that it can be used where the conventional high efficiency filters cannot be used because of the high pressure drop. The centrifugal filter can remove submicron particles from air of large volumetric flow rates at a high collection efficiency.

“Figure 1”

The collection efficiency of centrifugal filter, E, may be predicted by applying log-penetration law of Eq. (1). The single fiber collection efficiency, η, can be given as the sum of single fiber collection efficiencies due to interception, diffusion, inertia, gravity and centrifugal force, Eq. (2).

$$E = 1 - \exp\left(-{}^{4\alpha L\eta}/_{\pi(1-\alpha)D_f}\right) \quad (1)$$

$$\eta = \eta_{DR} + \eta_{IR} + \eta_G + \eta_C - \eta_R \quad (2)$$

where α is the packing density and D_f is the fiber diameter. The subscripts, R, D, I, G, C denote respectively interception, Brownian diffusion, inertia, gravitational setting and centrifugal force.

In the prediction of single fiber collection efficiencies due to (a) interception, (b) Brownian diffusion, (c) inertia, (d) gravitational setting and (e) centrifugal force, the following equations are employed.

(a) Interception, η_R:

Stekchina and Fuchs (1966) gave the following expression for interception single fiber efficiency.

$$\eta_R = \frac{1}{2}\frac{1}{h_k}\left[2(1+R)\ln(1+R) - (1+R) + \left(\frac{1}{1+R}\right)\right] \quad (3)$$

where R is the interception parameter defined by Eq.(4) and h_k is the hydrodynamic factor for Kuwabara flow (Kuwabara 1959).

$$R = \frac{D_p}{D_f} \quad (4)$$

$$h_k = -0.5\ln\alpha + \alpha - 0.25\alpha^2 - 0.75 \quad (5)$$

(b) Brownian diffusion and interception, η_{DR}:

According to Kirsch and Stekchina (1978), the single fiber collection efficiency due to Brownian diffusion and interception is given by the following equation.

$$\eta_{DR} = 2.9{h_k}^{-1/3}Pe^{-2/3} + 0.624Pe^{-1} + 1.24{h_k}^{-1/3}Pe^{-1/2}R^{2/3} + \eta_R \quad (6)$$

where Pe is the Peclet number. In Eq. (2), the interception efficiency of Eq. (3) is subtracted from the sum of $\eta_{DR} + \eta_{IR}$ because the interception effect is double-counted.

(c) Inertia and interception, η_{IR} :

Stechkina et al. (1969) gave the following expression for inertia-interception single fiber efficiency,

$$\eta_{IR} = 2{h'_k}^{-2}Stk\left((29.6 - 28\alpha^{0.62})R^2 - 27.5R^{2.8}\right) + \eta_R \quad (7)$$

where C_c is the Cunningham correction factor, u_0 the interstitial air velocity, ρ_p the particle density and the viscosity of air.

where Stk is the Stokes number defined by

$$Stk = \frac{1}{9}C_C\rho_p D_f u_0 R^2\left(\frac{1}{\mu}\right) \quad (8)$$

(d) Gravitational settling, η_G:

Yoshioka et al. (1972) gave the following expression for pure gravity.

$$\eta_G = G = \frac{v_t}{u_0} \quad (\because G \ll 1) \quad (9)$$

where G is the gravity parameter defined by the following equation.

$$G = \frac{1}{18}\frac{C_C D_p^2}{\mu}\rho_p\left(1-\frac{\rho}{\rho_p}\right)g\frac{1}{u_0} = \frac{v_t}{u_0} \tag{10}$$

where v_t is the terminal settling velocity, ρ is the density of air and g is the gravity.

(e) Centrifugal force, η_C:

Since the centrifugal force exerts on particles in a similar manner to the gravity, η_C is given by the following equation.

$$\eta_C = \frac{v_C}{u_0} \tag{11}$$

$$v_C = v_t\left(\frac{r\omega^2}{g}\right) = v_t Z_c \tag{12}$$

where Z_C is the centrifugal factor. In the calculation of centrifugal force, for simplicity, the rotation radius, r, is set equal to the arithmetic mean of inner and outer radii of filter, R_1 and R_2.

3. EXPERIMENTAL SETUP

A schematic diagram of the experimental set-up is presented in Figure 2. The diameter and length of centrifugal filter were 12.5 mm and 30 mm, which allows us to rotate the filter at the maximum rotation speed of ω = 3000 rpm using an AC motor (Panasonic Co., MBMS021BLS). Fixed inlet and outlet tubes with the inner diameter of 8 mm are connected with the centrifugal filter via rotary joints (Showa Giken Industrial Co. Ltd., RJ-RXE 1008 RH) (Fig. 1).

Table 1 shows the dimensions of centrifugal filter and the experimental conditions. According to the prediction of collection efficiency described in the preceding chapter, the filter (D_f= 10 μm, L = 30 mm, α= 0.01, u_0= 2.5 cm s^{-1}) without rotation has collection efficiency of 0.42 for 0.6-μm particles, and it is expected to increase to 0.95 at the rotation speed of ω= 3000 rpm.

As the filter media, stainless steel (SUS) fibers with fiber diameter of 10, 25 or 50 μm were packed in the annular part of the centrifugal filter. The packing density, α, of the fibrous layer was calculated from the mass of stainless fibers, w, by the following equation.

$$\alpha = \frac{w}{\pi(R_2{}^2 - R_1{}^2)\rho_f L} \tag{13}$$

where ρ_f is the density of SUS fiber. In the experiments, α was set at 0.01 by adjusting the mass of the packed SUS fibers but the local packing density would change due to the inhomogeneous packing and compression by the centrifugal force. Therefore in the prediction of the collection efficiency of the centrifugal filter, the effective packing density, α_{eff}, was determined experimentally by fitting the collection efficiency curves as explained later.

"TABLE 1"

Two types of test aerosol, *i.e.*, PSL and NaCl, were used for evaluating the collection efficiency of the centrifugal filter. Monodisperse polystyrene latex particles (PSL; JSR Co.) with the diameters of 0.5, 0.8, 1.0, 2.0, 2.5 μm were generated by atomizing the PSL suspension and passing through a diffusion dryer. Aerosolized PSL particles were electrically neutralized by passing through ^{241}Am neutralizer, and they were mixed with clean air and introduced to the centrifugal filter. The number concentration of PSL was measured by the optical particle counter (OPC; Rion model KC-01E) located at the inlet and at the outlet of the centrifugal filter. In the measurement of collection efficiency, the particle concentration was kept lower than 100 particles cm^{-3} so that the coincidence loss was negligible. The pressure drop, ΔP, was measured by a pocket-sized absolute pressure manometer (testo 511; Testo India Pvt. Ltd.).

NaCl particles were generated by the evaporation-condensation method. This type of test particles was used to evaluate the collection efficiency of the smaller sized particles (10 to 200 nm). In order to obtain the size-selected particles, the particles were classified by the differential mobility analyzer (DMA; TSI model 3081 long DMA) after acquiring a bipolar charge distribution with a ^{241}Am neutralizer. The mobility-classified NaCl particles (singly charged) were then introduced to another ^{241}Am neutralizer to be electrically neutralized. Monodisperse and electrically neutralized NaCl particles were mixed with clean air and introduced to the centrifugal filter as test particles. Nitrogen gas flow rate was about 1 L/min and the air flow rate was changed from 1 to 9 L/min. The number concentrations at the inlet and outlet of the centrifugal filter were measured by the condensation particle counter (CPC; TSI model 3775 CPC).

“Figure 2”

4. RESULTS AND DISCUSSION

Figures 3 show the collection efficiencies of centrifugal filter against the particle diameter at the fixed filtration velocity, $u_0 = 5.0$ cm s^{-1}. Three diameters of SUS fibers, D_f =10, 25, 50 μm, were used as the filter media. As shown in Fig. 3 (a), the collection efficiencies without rotation (open circles) are as small as 20% at the MPPS (most penetrating particle size) which is about 0.5 μm. The reason that the MPPS of centrifugal filter without rotation is larger than the usual one found in the conventional filters is that the fiber diameter used in our experiments is larger than 10 μm so as to attain low pressure drop. The collection efficiencies of particles larger than 0.5 μm are significantly improved by rotating the filter. At the maximum rotation speed of 3,000 rpm, the collection effciency of 1.36-μm PSL particles increases to 96%. On the other hand, the collection efficiency of the particles smaller than 0.2 μm did not changed due to the weak centrifugal force acting on the fine particles. As a result, the MPPS shifts from 0.5 μm (without rotation) to 0.2 μm (3,000 rpm). Figs. 3 (b) and (c) show the collection efficiencies of centrifugal filter composed of fibers with different fiber diameters (25 and 50 μm). It is concluded from these figures that the rotation of filter markedly improves the collection efficiency of particles larger than 0.2 μm even for the filter consisting of coarse fibers.

The solid lines in Fig. 3 (a) to (c) are the collection efficiencies predicted by Eq. (1). As mentioned previously, the effective packing density, α_{eff}, was determined experimentally by fitting the collection efficiency curves in diffusion-control regime. The effective packing densities, α_{eff}, under the best fitting, are 0.007, 0.01 and 0.02, for

10-, 25- and 50-μm fibers, respectively. The deviation from the mean packing density calculated from the packed mass of fibers ($\alpha = 0.01$) might be caused by non-uniform packing of the SUS fibers. As shown in Figs. 3 (a) to (c), the predicted lines well represent the size-dependency and the rotation-speed-dependency of the experimental collection efficiency. Therefore it is confirmed that the experimentally observed enhancement in the collection efficiency with rotating the filter is caused by the centrifugal force acting on the particles. As a consequence, we may use the log-penetration law of Eq. (1) to design the centrifugal filter.

"Figure 3"

Figures 4 are the plots of collection efficiency against rotation speed at the fixed filtration velocity, u_0, of 5.0 cm s^{-1}. As shown in Fig. 4 (a), the collection efficiency of 1.0-μm ($\rho_p = 1{,}053$ kg m^{-3}) particles increased with the rotation speed and it enhanced up to 80% for 10-μm fiber at the rotation speed of 3,000 rpm (current limit of experimental rotation speed). If the rotation speed could be increased further, the collection efficiencies might approach to 100% at the rotation speed of 4,000 rpm for 10-μm diameters of the fibers. On the other hand, in the cases of other two fiber diameters (25 and 50 μm), the collection efficiencies of 1.0-μm particles without rotation were almost zero, which means that the enhancement of the collection efficiency with rotation is caused solely by the centrifugal force. Therefore the higher rotation speed of about 6,000 rpm is necessary to capture all of the particles using the larger diameter of the fibers.

Fig. 4 (b) shows the collection efficiency of 0.2-μm particles against the rotation speed. As mentioned previously, the collection efficiency of particles smaller than 0.2 μm would not change under the present experimental conditions ($\omega < 3{,}000$ rpm). However, as shown in Fig. 4 (b), all of the 0.2-μm particles would be captured if the filter is rotated at higher rotation speed up to 15,000 rpm for 10-μm fibers and 20,000 rpm for 25- and 50-μm fibers. In fact, there are some commercially available aerosol measuring instruments in which the cylinder is rotated at a higher speed such as a centrifuge (e.g., APM; Kanomax Model 3601 APM-II, maximum rotation speed of 14,000 rpm). The key component to achieve such a high speed rotation is the rotary joint. In the present system, an air-tight rotary joint (Showa Giken Industrial Co. Ltd., RJ-RXE 1008 RH) was used but it would only withstand the maximum rotation speed of 3,500 rpm. In order to enhance the collection efficiency of smaller sized particles, the use of a rotary joint with magnetic fluid sealing would allow us to rotate the centrifugal filter at a rotation speed up to 20,000 rpm.

"Figure 4"

The other important characteristic of centrifugal filter is the pressure drop dependence on the rotation speed. Figure 5 shows the pressure drop of the centrifugal filter (fiber diameter of 25 μm) against the filtration velocity with the rotation speed as a parameter. As shown in Fig. 5, the pressure drop increases with the filtration velocity in the range of 0 to 15 cm s^{-1} and the curves are slightly concave against the filtration velocity. Since the Reynolds number calculated for the air by the fiber is less than unity, the dependence of pressure drop on the filtration velocity should be linear, suggesting that the pressure drop across the filter holder would dominate the total pressure drop of centrifugal filter because the pressure drop through the filter media is small. Even in this circumstance, the rotation of centrifugal filter causes only a slight increase in the pressure drop (< 100 Pa). The small increase in pressure drop by rotating the filter may be explained as follows. When the filter rotates, the air embedded in the filter also rotates with the fiber media. Therefore, no relative motion in the circumferential direction of filter rotation between the air and fibers would be added, and therefore the pressure drop is determined mostly by the relative motion between the air and fibers in the axial direction of flow. Consequently, the rotation of filter contributes mostly to the enhancement in collection efficiency while keeping the pressure drop as small as that of static filter.

Figure 6 shows the pressure drops of centrifugal filter consisting of fibers with different diameters as a function of rotation speed at a fixed filtration velocity of 5.0 cm s^{-1}. The pressure drop of path way without filter is shown black circles in Fig. 6. As shown in this figure, the curves of pressure drops plotted against the rotation speed are parallel to each other, suggesting that the resistance of filter media does not have any influence on the pressure drop increase with the rotation speed although the static filter with 10-μm fibers is higher than the other filter media with different fiber diameters (25 and 50 μm). What follows from Figs. 4, 5 and 6 are that we may increase the collection efficiency by rotating the filter while keeping the pressure drop increase minimum.

“Figure 5”

“Figure 6”

5. CONCLUSION

The present work proposed a new type of air filter, *i.e.*, the centrifugal filter, which significantly enhances the collection efficiency of submicron aerosol particles by centrifugal force. The enhancement of collection efficiency by rotating the fibrous filter was demonstrated experimentally and the dependences on rotation speed and filtration velocity as well as fiber diameter were well explained by the log-penetration equation using the single fiber collection efficiency accounting for the centrifugal force together with the conventional collection mechanisms. The pressure drop increase due to the filter rotation was so small that we can tune the collection efficiency of air filter by changing the rotation speed while keeping the pressure drop fairly invariant. Therefore the wide applications of the centrifugal filter in many fields are expected such as dust/mist separator, classifier, measurement instruments and so forth. Further increase in rotation speed may achieve classification of smaller particles.

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Figure captions

FIG.1. Basic concept of aerosol collection by centrifugal filter.

FIG.2. Experimental setup.

FIG.3. Collection efficiencies of centrifugal filter against particle diameter (u_0 = 5.0 cm s^{-1}, D_f = 10, 25, 50 μm). (lines are predicted by Eq. (1), and symbols are experimental data)

FIG.4. Collection efficiency of centrifugal filter against rotation speed at the fixed filtration velocity, u_0, of 5.0 cm s^{-1}.
(lines are predicted by Eq. (1), and symbols are experimental data)

FIG.5. Pressure drop of centrifugal filter against the filtration velocity with the rotation speed as a parameter.

FIG.6. Pressure drops of centrifugal filter consisting of fibers with different diameters as a function of rotation speed at a fixed filtration velocity, u_0, of 5.0 cm s^{-1}.

TABLE 1 Experimental conditions.

Inner radius, R_1 [mm]	5
Outer radius, R_2 [mm]	20
Filter length, L [mm]	30
Gas velocity, u_0 [cm s^{-1}]	2.5~15
Rotation speed, ω [rpm]	0~3000
Packing density, α [-]	0.01
Fiber diameter, D_f [μm]	10, 25, 50

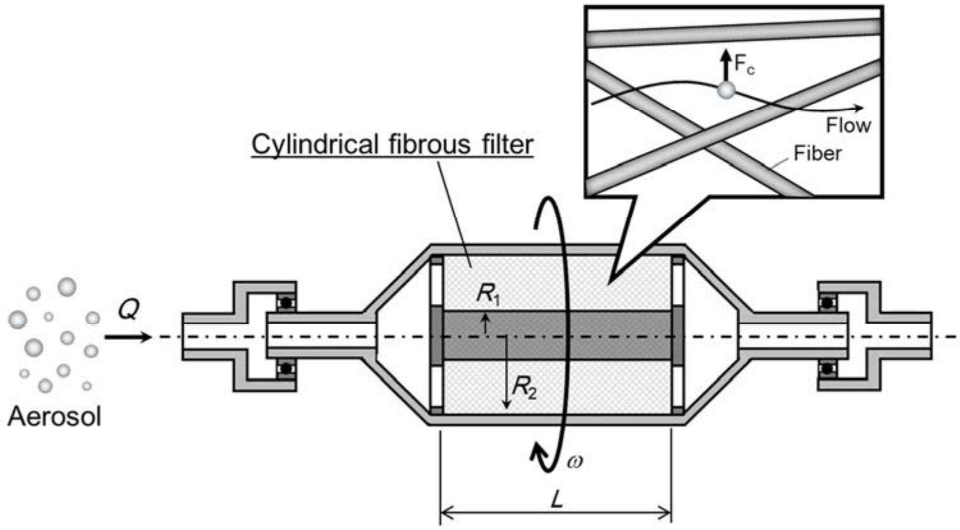

FIG.1. Basic concept of aerosol collection by centrifugal filter.
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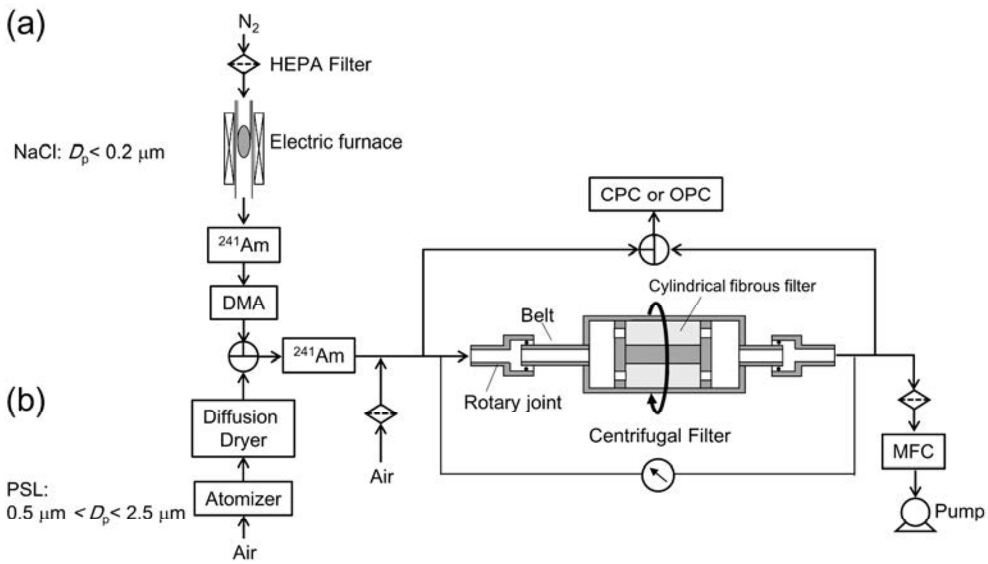


FIG.2. Experimental setup.
793x595mm (96 x 96 DPI)

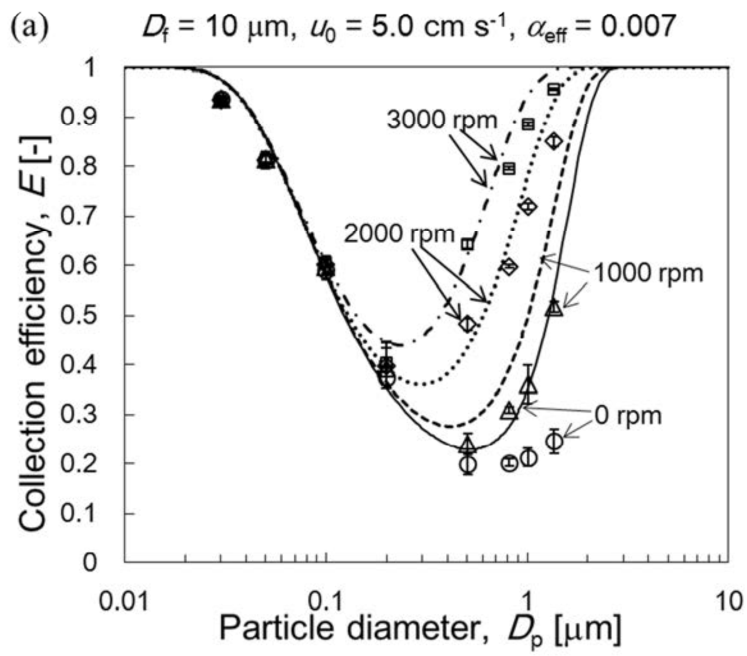
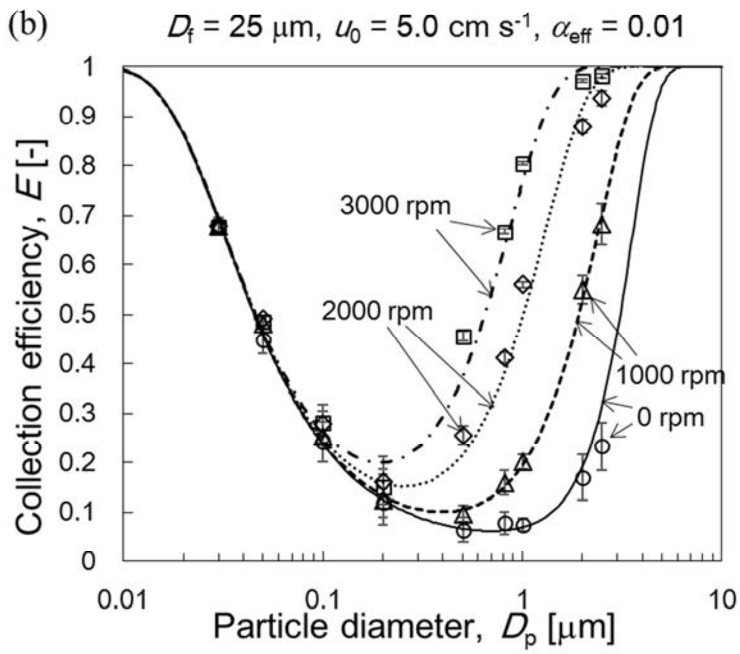


FIG.3. Collection efficiencies of centrifugal filter against particle diameter (u_0 = 5.0 cm s^{-1}, D_f = 10, 25, 50 μm).
(lines are predicted by Eq. (1), and symbols are experimental data)
793x595mm (96 x 96 DPI)



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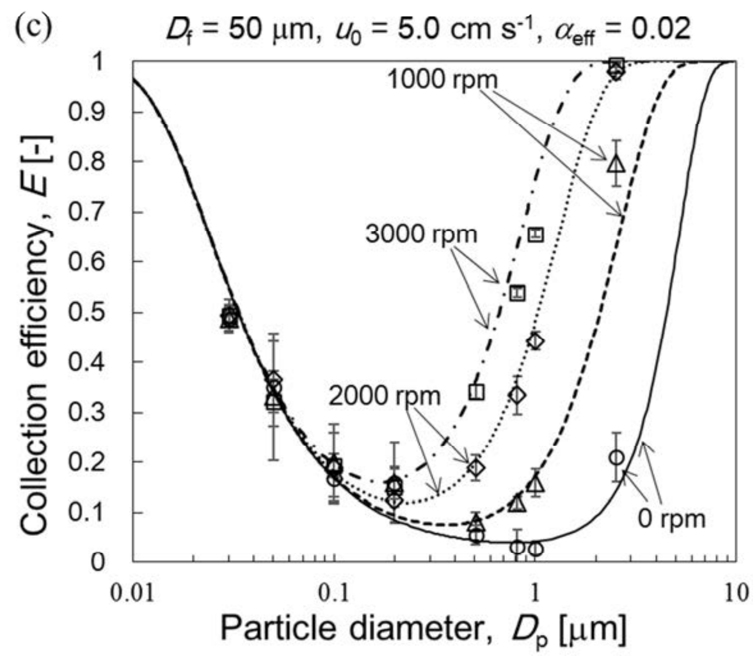

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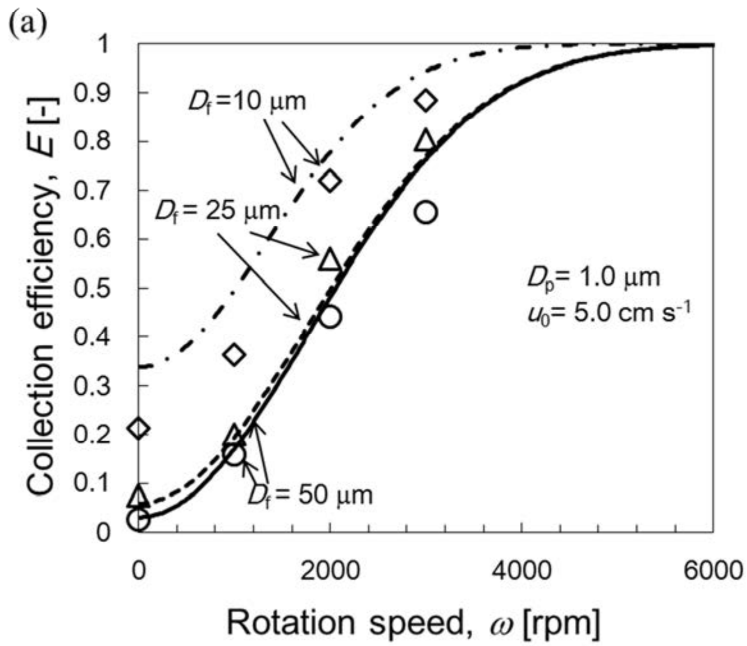

FIG.4. Collection efficiency of centrifugal filter against rotation speed at the fixed filtration velocity, u_0, of 5.0 cm s^{-1}.
(lines are predicted by Eq. (1), and symbols are experimental data)
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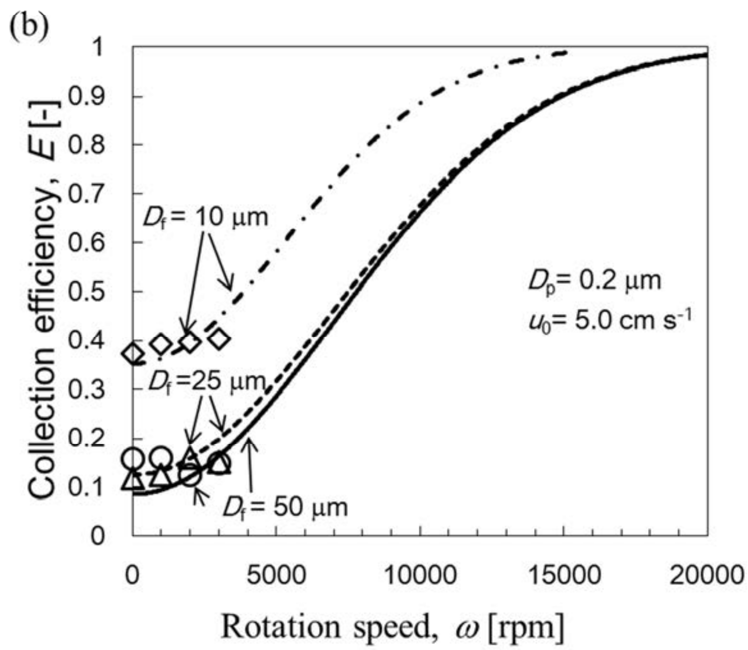

FIG.4. Collection efficiency of centrifugal filter against rotation speed at the fixed filtration velocity, u_0, of 5.0 cm s^{-1}.
(lines are predicted by Eq. (1), and symbols are experimental data)
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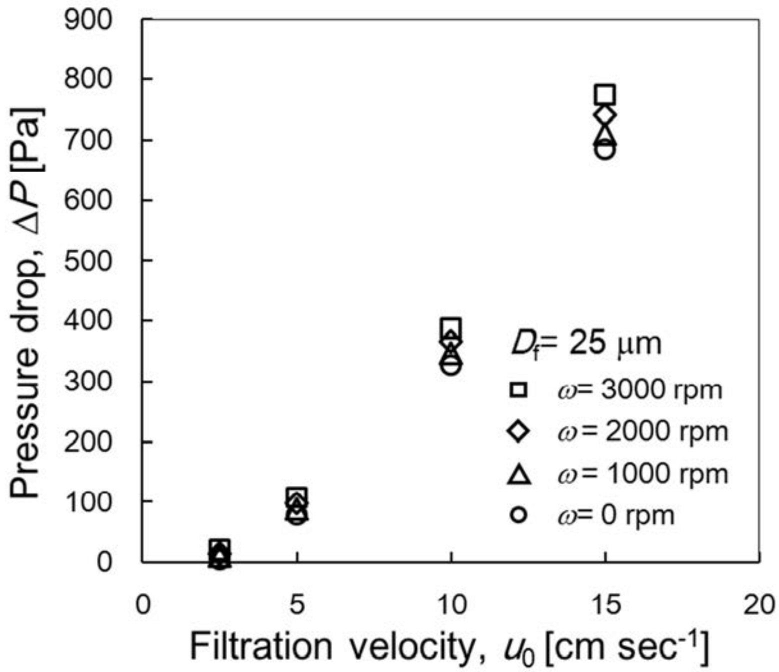

FIG.5. Pressure drop of centrifugal filter against the filtration velocity with the rotation speed as a parameter.
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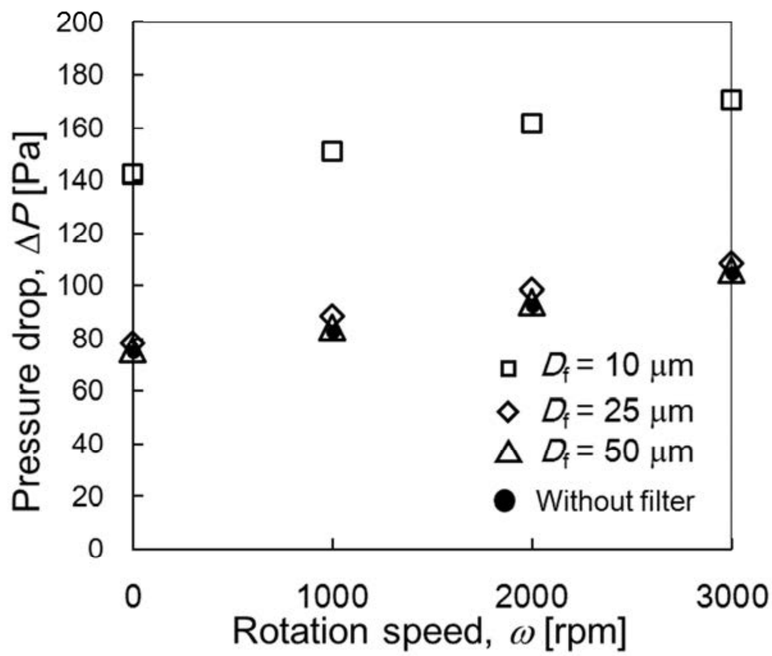

FIG.6. Pressure drops of centrifugal filter consisting of fibers with different diameters as a function of rotation speed at a fixed filtration velocity, u_0, of 5.0 cm s^{-1}.
793x595mm (96 x 96 DPI)